GROUND-ICE WEDGES

THE DOMINANT FORM OF GROUND-ICE ON THE NORTH COAST OF ALASKA

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It is a widely known fact that the ground in Arctic and sub-Arctic regions is permanently frozen to a great depth, only the upper few feet thawing in summer. Nearly all observers have reported the presence of bodies of more or less clear ice underlying the surface of the ground, usually immediately below the limit of annual thawing. Ordinarily the ice is represented as existing in horizontal beds of some thickness and lateral extent, but the observations of the writer upon the north shore of Alaska show that there, at least, the ground-ice occurs chiefly in a network of vertical wedges, surrounding isolated bodies of the tundra formation.

Although this form of ice is the dominant one in the area studied, it is not held that it is the only one, nor that the theory of its formation will fit every case. It seems quite certain that there are several different kinds of ground-ice, each one having originated in a different way.

During the summer of 1914 several dozen photographs of the ice were made, but most of them were damaged later by water, so that the writer has to depend chiefly upon sketches which were often hastily made. Fortunately Mr. P. S. Smith, of the United States Geological Survey, had, some years ago, secured photographs of ground-ice on the Noatak River, and one of these photographs illustrates the wedge-form ice which is the subject of this paper (Figs. 1, 2).

The chief difficulty encountered in the study of the tundra formation arises from faulty exposures. The ground being of material only consolidated by frost, a short exposure to the summer air will cause slumping and consequent masking of the details. It is only where wave or river action has undermined the face of a bank, so that large blocks break off, that good exposures are formed. As

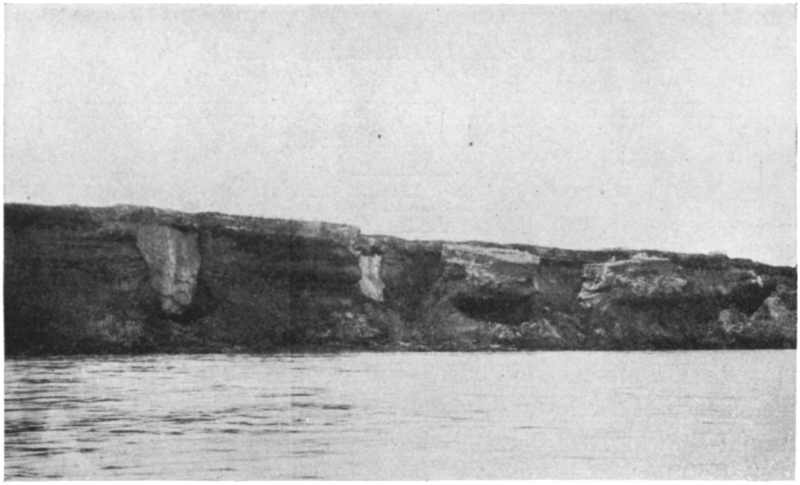

FIG. 1.—Ice wedges, Noatak River. Photograph by P. S. Smith, U.S. Geological Survey.

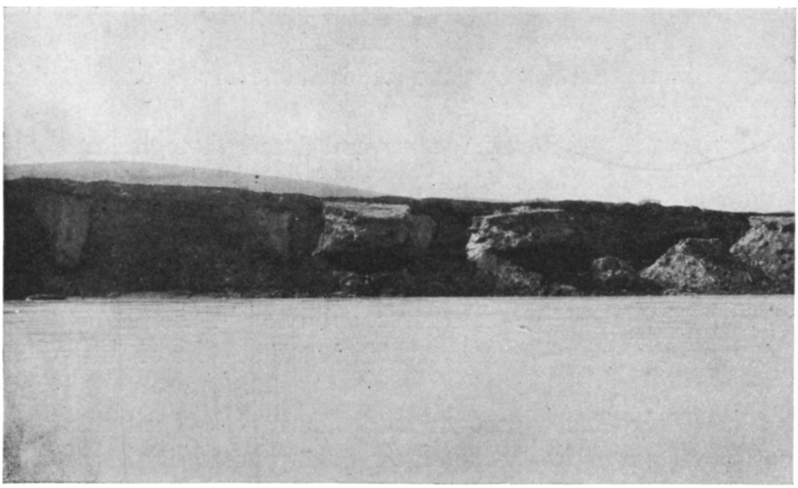

FIG. 2.—Another view of exposure shown in Fig. 1. Photograph by P. S. Smith, U.S. Geological Survey.

soon as slumping has taken place, erroneous conclusions may be drawn as to the distribution of the ice, scattered outcrops being interpreted as exposed parts of a single bed.

The upper surface of the ground-ice is usually only a foot or two under the surface of the tundra. Consequently in an area which has discontinuous bodies of ice separated by masses of muck, etc., there will be the least amount of material for slumping exactly where the ice occurs. The ice melts back under the overhanging turf, forming a cave, but at either side the muck will slump from

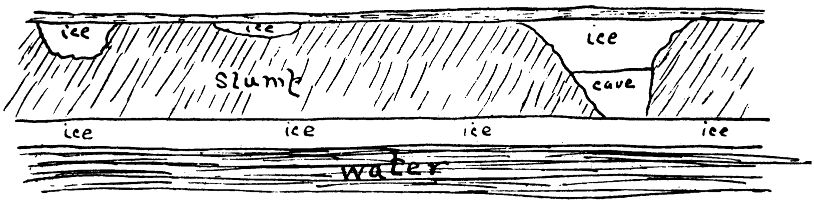

FIG. 3.—Exposure of a bank showing an apparently continuous thick bed of ice

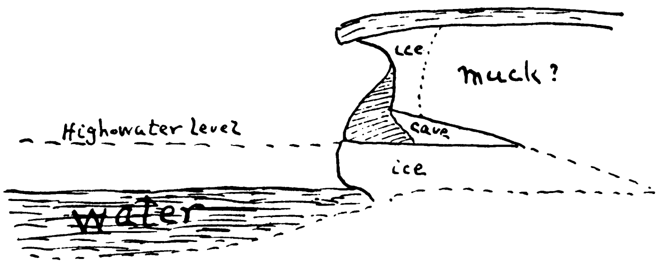

FIG. 4.—Structure of exposure in Fig. 1

the grass roots. Thus, wherever the surface of the bank is exposed, ice is likely to be seen, and observers are led to believe that a continuous body of ice underlies the whole area.

In addition to the erroneous impression as to lateral extent, the conclusions as to thickness are also often faulty. A winter's snow drift against the foot of a bank may be covered by slumping and later exposed, apparently showing a thickness of ice only limited by the height of the bank. The same may be true of river- or sea-ice. An illustration is given of an apparently continuous bed of heavy ice which the writer examined carefully for a quarter of a mile before learning its true nature (Figs. 3 and 4).

The waves had undercut this bank the summer before, making a long, low cave, perhaps ten feet deep. During the following winter this cave had been flooded at high tide and partially filled with ice. Early in the summer the face of the bank had been masked by slumping, leaving only a few glimpses of true ground-ice under the turf. Shortly before the time of observation the lower part of the bank had been washed clear of débris, exposing the continuous layer of new sea-ice. This appeared to be ground-ice, when coupled with the scattered exposures of undoubted ground-ice above. Luckily the cave was exposed to view at one point, so that the mistake in interpretation could be corrected.

The writer went into the field in the summer of 1906 with the idea that the coastal ground-ice occurred in horizontal sheets, and in consequence of faulty exposures did not learn its real distribution until 1914. During the first eight summers, although the ground-ice was examined at every opportunity, little insight was gained into the method of its formation. There has been no opportunity to go anew through the literature before writing this paper, but such illustrations as are at hand do not bear out the inferences drawn from them as to large horizontal beds of ice.

The usual theory advanced in the literature is that bodies of snow or ice were buried by peat or wash material and thus preserved. The writer sought to interpret the Alaskan coastal ground-ice in the light of this theory, but could neither postulate a satisfactory source for the ice, nor find any workable hypothesis to account for its preservation. It was not until the summer of 1914 that the fact was forced upon him that most of the ice was formed in place in the ground. A vertical wedge of ice within a peat bed first drew his attention to the fact; for such a dike of ice could not have stood up in the air for the hundreds of years that were necessary for the formation of the peat (Fig. 5).

FROST CRACKS

During the Arctic winter, frequent reports are heard, coming apparently from the ground. Often the sound is accompanied by a distinct shock, which is in fact an earthquake of sufficient intensity to rattle dishes, etc. One is justified in ascribing this phe-

nomenon to the cracking of the frozen ground during the winter's contraction. The writer has spent six winters in the region under discussion, living most of the time upon the tundra, which is chiefly underlain by muck. Frequent camps have been made upon other formations, such as sands and silts, and the impression carried away is that the sound of the cracking ground was heard everywhere. This has been confirmed by a prospector who has lived nearly thirty years in the country.

It was at first thought that the reports were caused by the cracking of hard snowdrifts, but the fresh cracks in these drifts were seen to run into the ground below. When the snow melts in the summer,

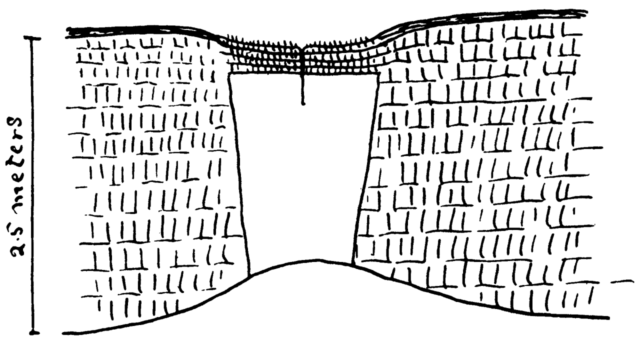

FIG. 5.—A large ice wedge in peat beds. The peat beds are not upturned. The ice is capped by growing moss.

fresh open cracks can be seen cutting across all the tundra formations, even mud and growing moss beds, and dividing the surface into polygonal blocks; these cracks resemble mud cracks but are of a larger size. The blocks have an estimated average diameter of about 15 meters, and have a tendency toward the hexagonal form, although rectangles and pentagons are often developed.

Occasionally a crack is seen to run across a flat surface with no associated features, as is illustrated in Fig. 6, but usually it is accompanied by a distinct topography. Either the crack lies in a gentle depression which surrounds an elevated polygon block, or it runs between two parallel ridges which surround a depressed block. These features do not vary from block to block, but each is locally developed over a considerable area. The "elevated blocks" have

seldom a relief of more than one foot, but that of the "depressed blocks" may be twice as much.

The parallel ridges form shallow reservoirs, very similar to those of the block system of irrigation, especially when they take a rectangular form, as is often the case. They often contain ponds and are always swampy, so that one keeps to the ridges for dry footing when crossing such an area (Figs. 7 and 8).

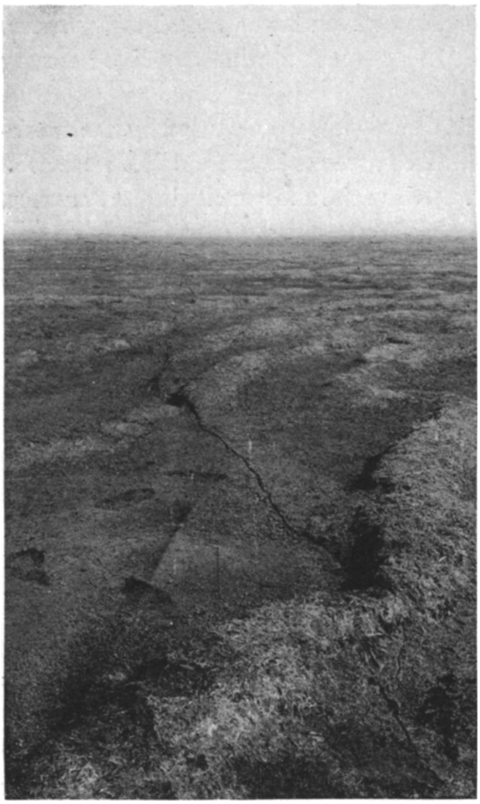

FIG. 6.—A frost crack on the surface of a recently drained area.

FORMATION OF ICE WEDGES

The open frost crack is in a favorable position for being filled with water during the melting of the snow, for most of them lie in depressions upon a flat surface. Even those that by chance get no water probably become filled with ice crystals deposited by the damp air, by internal "breathing." The crack, being filled with solid ice from the freezing of the water, or containing much ice in the form of frost crystals, thus contains a narrow vein of true ground-ice in the portion which lies below the depth reached by the annual thawing. When the frozen ground expands under the summer's heat, the readjustment to the strain may take place in four ways: (1) The pressure may melt the ice, so that the crack is closed again. (2) The formation

FIG. 7.—A frost crack lying between parallel ridges which inclose depressed polygon areas.

FIG. 8.—Frost cracks, parallel ridges, and block ponds

may be sufficiently elastic to absorb the strain, so that no deformation occurs. (3) The formation may be deformed and bulged up, either as a whole or locally along the edge of the ice wedge. (4) The ice may be deformed.

If the summer's strain has been relieved by readjustment of the material within the polygon block, the next winter will again bring about the conditions which caused the first cracking of the ground. Even if the first crack is full of ice, it may be still a plane of weakness for tensive strains; and this will be especially true if the crack has been only partially filled. Granted that it is a plane of weakness, the new cracks will open at the same place and a constantly growing body of ice be formed at the locus. That this is the ordinary case in tundra formations is seen in the constant association of ice wedges with definite loci of frost cracks.

Thus the growth of the ice goes on from year to year, possibly failing during mild years, when it may not be necessary for all the cracks to open in order to relieve the strain. If the process were not hindered, the upper edges of the wedges would eventually come into contact, thus completely inclosing a cone-shaped mass of the original ground-material. It is conceivable that the process might still go on by bulging up the ice, as it at first bulged up the ground. It is thus within the limits of possibility that a continuous horizontal bed of ice should be formed in this manner, but nothing approaching this possible stage has been observed by the writer.

The thinnest wedge that has come under observation was about a foot wide, but cracks have been seen accompanied by no surface manifestations (Fig. 6) and with no visible ice below them. No doubt the intervening stages exist, especially in an area such as a recently drained lake bottom, where the process is being initiated. The thin veins have nearly parallel sides and flat tops, as can be seen in Figs. 9 and 10. As the ice increases in size, it becomes more wedge-like in form, since the growth is greatest near the top where the crack opens widest. There is a tendency in the large wedges to spread out under the surface of the ground (Fig. 11). This is exaggerated in oblique sections, as is shown in Fig. 12.

The bottom of an ice wedge has never been observed by the writer. Most of the banks on the north shore of Alaska are less

than ten feet high and the bottom is nearly always concealed by slumping. The maximum vertical dimension observed is about 3 meters, but the wedge had a thickness sufficient to have carried it two or three times as far down before pinching out. The ultimate

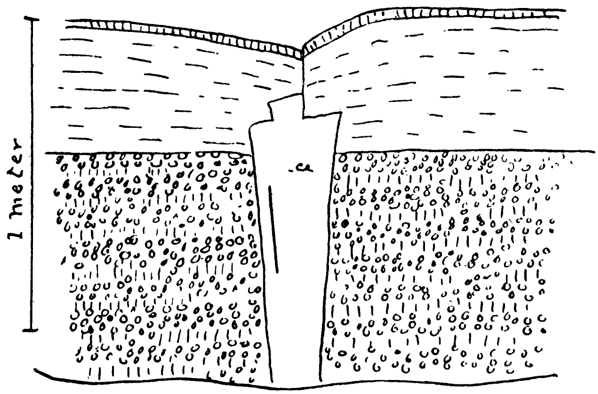

FIG. 9.—A narrow ice wedge in a deposit of mixed clay and ice granules. An open crack within the wedge.

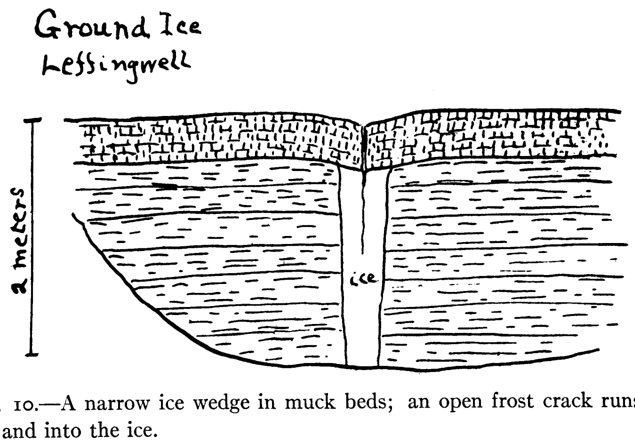

FIG. 10.—A narrow ice wedge in muck beds; an open frost crack runs through the turf and into the ice.

depth must depend upon the depth of annual change in ground temperature in the region. The constants are so uncertain that it is impossible to make a close calculation of this depth. For the purposes of this paper the depth of the ice wedges is assumed to be from 8 to 10 meters.

The upper surface of the ice is usually less than two feet under the ground in muck formations, about the limit to which the summer's thawing penetrates. This surface is usually horizontal, or undulating with the surface of the ground. One or two exposures showed a dome-shaped surface, and another, a central projection above the general surface (Fig. 9). Some more complicated exposures are shown in Figs. 12 and 13. The overlying material is usually muck capped by a few inches of turf. Occasionally it is peat capped by growing sphagnum (?) moss.

Without going deeply into the question of the crystallization of ice, it may be remarked that ice resulting from snow (and glaciers)

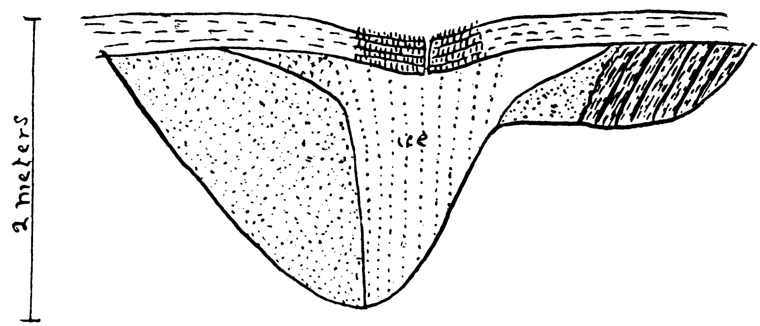

FIG. 11.—A large ice wedge which spreads out under the surface of the ground. The vertical lines indicate rows of whiter ice full of air bubbles. The material on either side is sand. To the right are upturned muck beds.

is granulated, but that from standing fresh water is vertically prismatic. Sea-ice is different from both, but very little has been written upon the subject. The writer's own observations are that sea-ice loses its salt at temperatures approaching $0°$ C. and becomes honeycombed, showing a general vertical structure, but decidedly different from that of fresh-water ice.

A fresh transverse section of an ice wedge shows a face of whitish ice with numerous parallel vertical markings (Figs. 11–14). These markings are usually of whiter ice which is seen to contain an unusual amount of air bubbles. It is often visibly granular, yet shows a general vertical structure, and breaks up into short, irregular pieces when allowed to melt slowly in the shade.

At the sides of the wedge the markings of the ice are inclined from the vertical and approach parallelism with the sides. Since the growth seems to occur near the center of the wedge, the older lines, though originally vertical, are later spread apart at the top. Oblique sections of wedges will give exaggerated angles of inclination or even curves (Figs. 14 and 15).

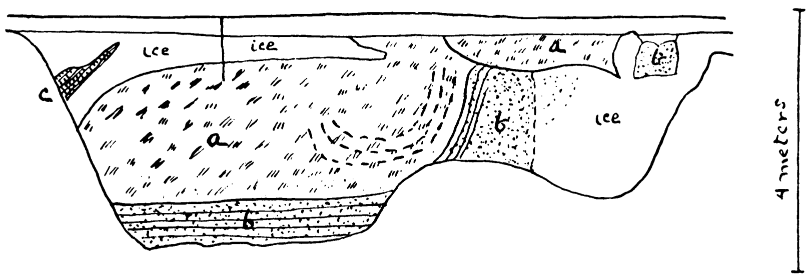

FIG. 12.—A complicated exposure: *a*, disturbed muck and clay; *b*, clay; *c*, peat; at *d* a frost crack runs through the turf and ice.

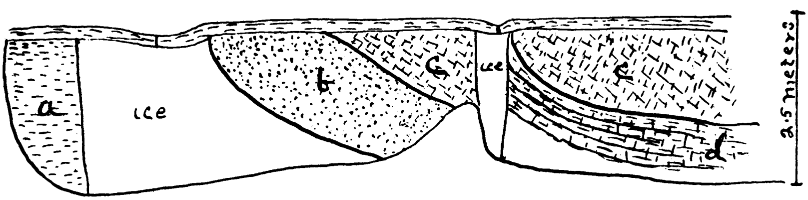

FIG. 13.—A complicated exposure: *a*, clay; *b*, sand; *c*, peaty detritus, no structure visible; *d*, peaty detritus.

In several cases open cracks were seen running down for a few feet into the ice, often being a prolongation of an open frost crack in the tundra above. Once or twice open cracks were seen within the body of the ice, so that a thin sheath knife could be shoved in for several inches (Figs. 9 and 10). Near the edge of a bank these open cracks may become drainage lines for surface waters, so that a tunnel is developed within the ice (Fig. 16). As the tunnel widens the roof caves in and a deep gully is formed in the bank. These gullies work back and around the polygon blocks, making the neighborhood of an old bank rather difficult walking.

The typical formation associated with ice wedges in the region under discussion is muck, a black mud containing much vegetable matter more or less decomposed. It varies from a peaty detritus, which shows signs of having been waterlaid, to sand or mud mixed with a varying amount of decaying vegetation. Undisturbed sections of this muck will usually show horizontal bedding. Occasionally sand or a slimy clay was seen under the muck where a good exposure revealed the lower strata (Fig. 12). As the ice wedge grows in thickness and presses against the edges of the cleaved muck and sand beds, they may become upturned and in time bent to the

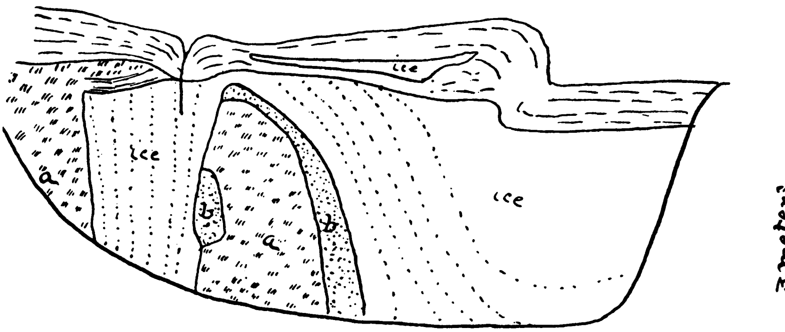

FIG. 14.—Two joining wedges; the one on the right is cut obliquely. The dotted lines represent lines of air bubbles within the ice. *a*, muck and clay, much disturbed; *b*, sand. See Fig. 15.

vertical or even beyond (Figs. 12, 17 and 18), causing the ridges which often run along either side of the frost crack in "depressed block" areas. In "elevated block" areas, the process is not so easily understood. It may be that the block as a whole has bulged sufficiently to bring its surface up to the general level, or else a central depression has been filled by growth and capped by turf.

The writer's observations were insufficient to disclose the factors which control the character of block development. The "elevated blocks" are characteristic of drained areas and are nearly constant features near banks. The "depressed blocks" are associated in the writer's mind with flat, marshy country. This, however, may be the effect rather than the cause of the difference in character of the blocks. The network of depressions drains the elevated blocks, but the ridges form dams which interfere with surface drainage.

As the growing vein of ice becomes more wedge-like in form, the pressure exerts a vertical component against the sides of the wedge. This tends to force the wedge upward. If an upward movement should occur, the ice would carry its protective covering with it and be able to exist level with or even somewhat above the general surface of the block. Since a bulging of the block by the growing wedge seems necessary, some upward motion of the wedge may have taken place without bringing the top of the wedge up to the

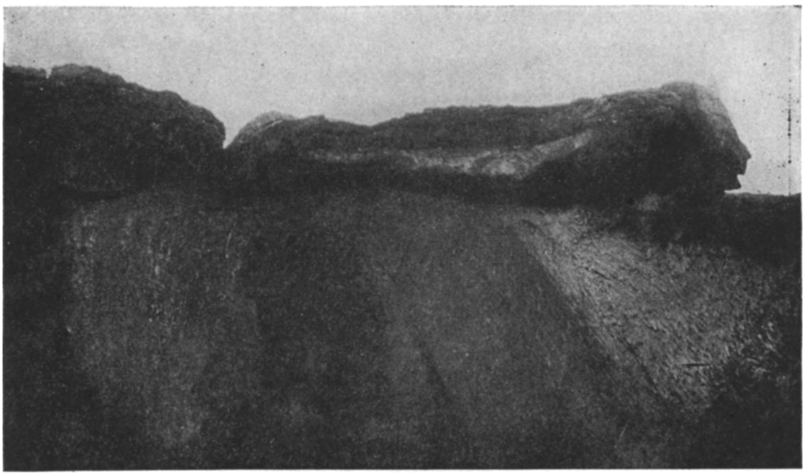

FIG. 15.—Photograph of exposure shown in Fig. 14

general level. In the depressed blocks it is to be noticed (Figs. 7 and 8) that the surface of the ground between the parallel ridges (probably underlain by ice) is higher than that of the blocks on either side. No exposures were found illustrating this case, so it is impossible to say whether the surface of the ice is actually higher than that of the blocks.

The usual covering for the ice is muck capped by turf, or peat capped by growing sphagnum (?) moss. As the thickness of this mantle increases by surface growth, the limit of the summer's thawing should rise, thus allowing a constant upward extension of the surface of the ice wedge at the locus of growth. Only two or three cases of apparent upward growth of the surface were seen. In one

case (Fig. 9) there is an upward projection of ice above the general surface of the wedge, indicating a sudden change of the limit of thawing. The others showed a dome-shaped surface, indicating a gradual change. Since the majority of exposures show the surface of the wedges to be nearly parallel with the surface of the ground,

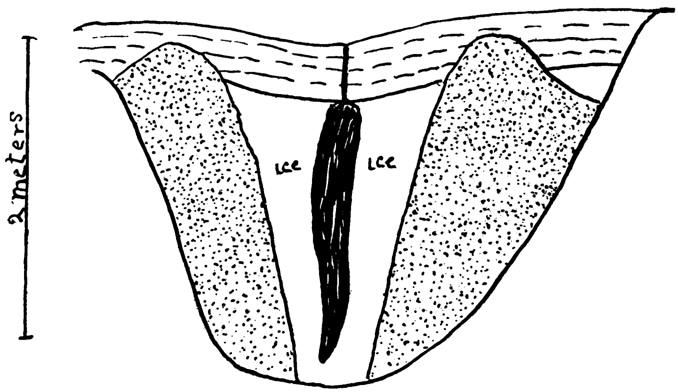

FIG. 16.—An ice wedge in sand. A tunnel has been cut in the ice by drainage of surface waters through the frost crack. The sand on either side is apparently bulged.

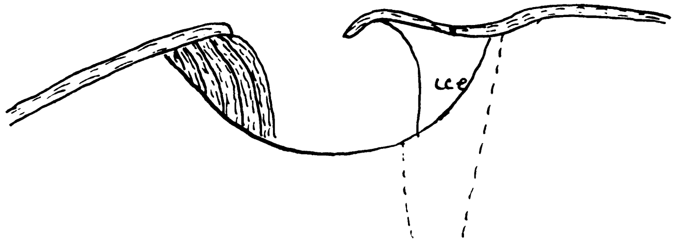

FIG. 17.—Section perpendicular to a bank, showing upturned muck beds in a tundra block which has broken off along an ice wedge.

it seems that a balance must be maintained between the thickness of the covering and the increase in area to be covered, as the wedge becomes wider.

The rate of growth of turf must be very slow in this region, for there are many half-buried bowlders on the surface of the tundra, which have been there since glacial times, or at least since the coastal plain emerged from the sea. Many bare spots exist where the turf has not been able to get a footing.

Where the protective covering is of muck, creeping of the soil will tend to close up the open frost crack. This will thin the covering, and if the rate of surface growth is not sufficient to counteract the resulting decrease in thickness, the upper surface of the ice will be lowered by melting. The increased slopes will cause side material to creep down over the ice, thus keeping the protective mantle up to the required thickness. A shallow depression will thus be formed whose slopes are of the proper angle to cause the proper amount of creeping.

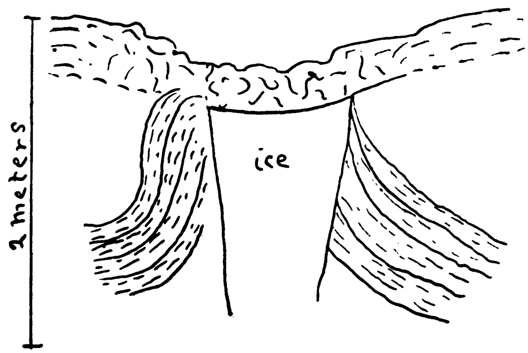

FIG. 18.—An ice wedge in muck showing upturned strata

In the case of sphagnum (?) moss the case may be somewhat similar. The moss and subjacent peat may also close the crack by creeping. At the same time the bed will become thinner, but growth of the moss will soon thicken it again. If the moss grows too fast, the depression will be filled and the conditions of moisture favorable to growth will cease. Thus it is possible for the growing ice wedge to have a covering of peat of constant thickness.

When a bank is undercut by wave or river action, large masses of tundra often break off. Since the ice wedges are planes of weakness, the break is along the edges of the polygon blocks, whenever this is possible. This is especially true of high banks, where whole blocks will break out, leaving many re-entrant angles in the resultant bank, along which a nearly continuous exposure of ice may be seen. The impression is carried away of a heavy horizontal sheet

of ice of great thickness, whereas, in fact, little of it extends back more than a few feet from the face of the exposure (Figs. 19, 20, and 21).

In Fig. 22 is shown a plane-table map of an area of frost cracks, and a sketch of the exposures of ground-ice in the bank immediately below. The polygon blocks were of the elevated type, but the relief was very faint, being somewhat obscured by sand which had drifted up from a sand spit on the left. The exposure was somewhat slumped, but gave sufficient details to illustrate the case.

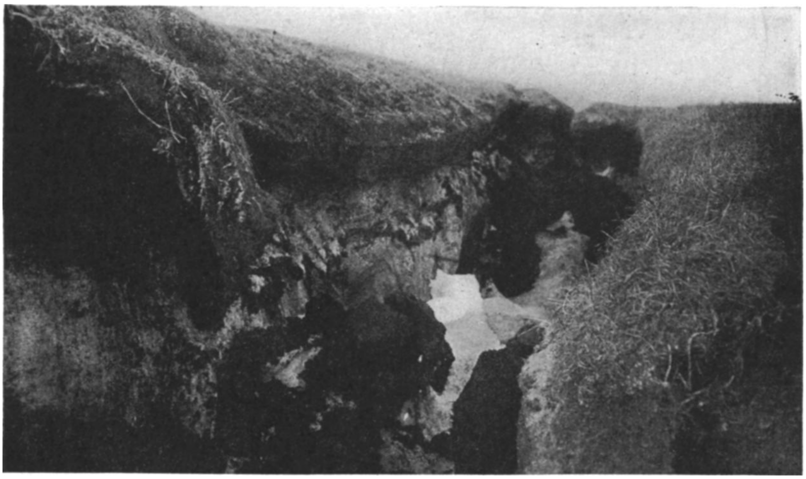

FIG. 19.—Exposure of ice extending some distance inland. A tundra block is breaking off along an ice wedge.

The heavy lines on the map show open frost cracks; the dotted lines, the evident loci of cracks. Where there was no surface indication, no lines were drawn. The shaded areas are supposedly underlain by ice wedges.

Ground-ice occurs at the intersection of every crack with the bank, where the details were not masked by slumping.

The average diameter of eleven blocks shown on the map is about 11 meters. The largest block is about 11 by 15 meters, and the smallest 5 by 8 meters. The largest wedges of ice are about 2.5 meters wide at the top, and this width has been used in indicating the areas probably underlain by ice, except where surface

indications pointed to new loci. About 20 per cent of the tundra is found to be probably underlain by ice of greater or less thickness.

On a 250-mile boat trip from Flaxman Island to Point Barrow in the summer of 1914, good exposures of muck banks always revealed ice. Many miles were examined closely on foot or from the boat, and very little ice was observed which was not definitely in the form of vertical wedges associated with frost cracks on the surface of the tundra.

FIG. 20.—Tundra block broken off. Ice wedge at left

Ground-ice wedges with their accompanying surface features are typically associated with muck formations, and none were seen elsewhere. River silts, elevated sand and gravel deposits, and soft shales have been carefully examined and the only ice found in such places was evidently of another form and of a different origin. Straight lines leading across the gentle surface undulations of sand spits have frequently been observed, and they could be explained only by frost cracks. No polygonal forms have been seen in such places. The writer is unable to say whether ice wedges develop in such sands, for the exposures made by fresh wave-cutting are seldom more than 2 or 3 feet deep, which is less than the depth reached by the summer's thawing.

RATE OF GROWTH OF WEDGES

Fresh ice-filled cracks 8–10 mm. wide have been observed in the ground immediately above the ice wedges. This may be put as the maximum width of the crack. Open cracks about 5 mm. wide have been found in the ice itself near the upper surface. The width, of course, diminishes downward. If 5 mm. is assumed as the width at the top, it would require only 600 years to build up a wedge 3 meters wide, which is about the maximum width seen in the region.

FIG. 21.—A large tundra mass broken off along the sides of a polygon block. The ice has mostly melted away.

If the cracks do not all open every winter, this period must be multiplied by some factor. The writer had frequently observed open cracks during the previous years, but not realizing their bearing, did not keep any record of their abundance. About 1,000 years seems to be the order of age of the largest wedges. Unless some unknown cause prevents a greater growth, the temperature could not have been sufficiently low to bring them into existence at an earlier date, or else the coastal plain has not been elevated above sea-level for a longer period.

If we assume that the elevated blocks are bulged by the growing ice, the amount of general elevation of the surface of the tundra can

readily be calculated. If 20 per cent is taken for the surface compression of the block, the average compression will be 10 per cent. An average block 11 meters in diameter will be compressed horizontally 1.1 meters to an assumed depth of from 8 to 10 meters. This will cause an increase in a vertical direction of about 1 meter.

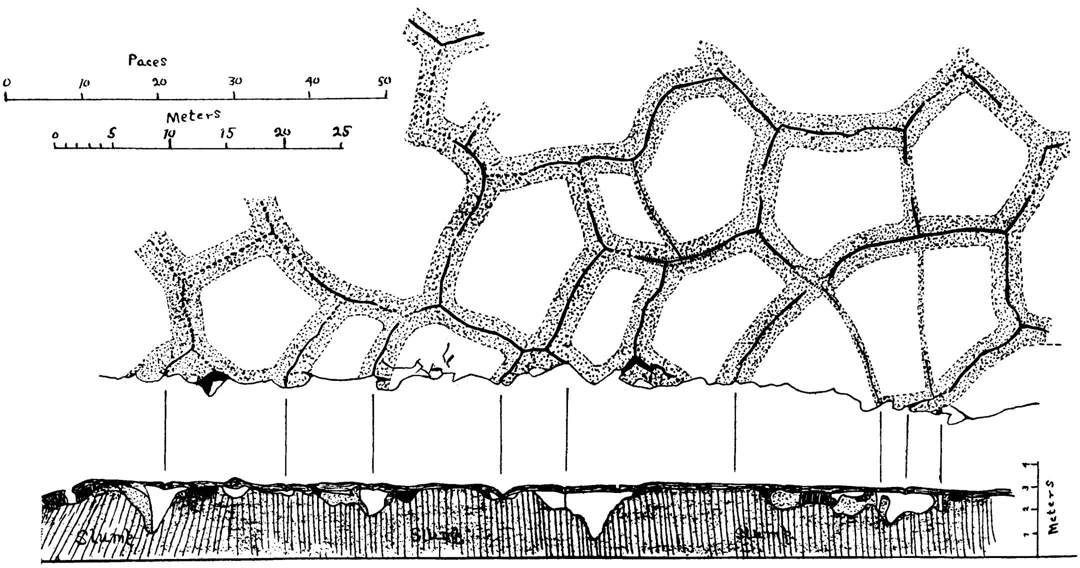

FIG. 22.—Planetable map of frost cracks on the tundra, with a sketch of the exposures of ground-ice in the bank at one edge of the mapped area.

The heavy lines on the map represent open frost cracks in July. The dotted lines indicate evident frost-crack loci. The stipple marks show the areas probably underlain by ground-ice.

In the section below the map, the white spaces represent ground-ice, the dotted spaces, sand. The rest of the exposure has slumped.

The case is different with the depressed blocks, where the adjustment is concentrated into the ridges that surround them. The depressions are being continually filled with growing vegetation, as well as picking up wind-blown material, thus forming muck beds. In this way a much greater general elevation of the surface of the tundra is possible. Much of the muck of the region may have been developed in this way.

The principle of the development of ground-ice wedges is capable of widespread action throughout the region of permanently frozen ground. It is so persistent on the north shore of Alaska that it is to be expected to come into play in similar regions elsewhere. The writer is inclined to believe that much of the ground-ice described in the literature as in horizontal sheets may turn out to be in vertical wedges. In the classical locality at Eschscholtz Bay, no one observer agrees with the others. One says that there is a solid mountain of ice, while a second finds only a thin veneer of ice against the face of the bank. A more careful observer finds scattered outcrops of ice, including at least one vertical dike. In other regions "polygon marks" and vertical markings upon whitish ice are mentioned.

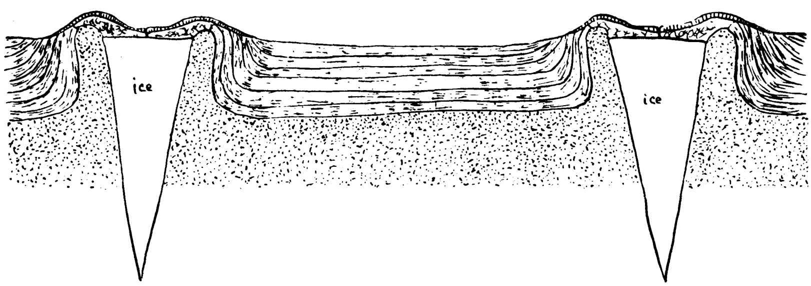

FIG. 23.—Hypothetical section of ice wedges and depressed polygon block

SUMMARY

The permanently frozen ground contracts in the cold Arctic winter and cracks are formed, which divide the surface of the ground into polygonal blocks. In the spring these frost cracks become filled with surface water which immediately freezes. In the expansion of the frozen ground as its temperature rises in summer, the vein of ice being more rigid than the country formation, the readjustment takes place in the latter. The result is to bulge up the inclosed block either bodily or else locally along the sides of the ice. During the next winter's cold wave, a new crack forms at the same locus, so that a continually growing wedge of ground-ice is formed (Fig. 23). Thus the tundra becomes underlain by a network of ice wedges, which inclose bodies of the original formation.